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Comparison of renewable fuels based on their land use using energy densities

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ABSTRACT

In this article energy densities of selected renewable fuels are determined. Energy density is defined here as the annual energy production per hectare, taking energy inputs into account. Using 5 scenarios, consisting of 1 set focusing on technical differences and 1 set focusing on geographical variations, the range of energy densities currently obtained in Europe was determined for the following fuels: biodiesel from rapeseed; bioethanol from sugar beet; electricity from wood, wind and solar PV.

The energy densities of the fuels produced from biomass were calculated by determining the energy contained in the energy carrier produced from the crop annually produced on 1 ha, from which the energy inputs for crop cultivation and conversion were subtracted. For wind and solar electricity, the energy density calculation was based on the energy production per turbine or cell and the number of turbines or cells per hectare after which the manufacturing energy was subtracted.

Comparing the results shows that, for the average energy density scenarios, the ratio between the energy densities for wind, solar, and biomass is approximately 100:42:1, with wind electricity also having the highest energy output/input ratio.

A case study was done in which the energy density was used to calculate the distance a vehicle can cover using the energy carrier annually produced per hectare. This was done for 3 regions, in Mid-Sweden, North-Netherlands, and South-East Spain. The results of the case show that wind electricity results in the largest distance covered, except in Spain, where solar electricity is the most favourable option.

Contents

1. Introduction

The emission of greenhouse gasses, mainly CO_2, produced in the combustion of fossil fuels is generally considered one of the drivers of climate change. Given the potentially catastrophic consequences of climate change, and because the European Union (EU) is

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Table 1
List of renewable energy sources used.

Energy carrier	Source
Biodiesel	Rapeseed
Bioethanol	Sugar beet
Electricity	Wood
Electricity	Wind
Electricity	Solar PV

a major source of CO_2 emissions, producing approximately 12% of the total worldwide CO_2 emissions [1], the EU aims at introducing renewable fuels in the energy systems of its member states. A target of introducing 20% renewable fuels in the EU energy mix by 2020 has been set, as well as the target of a 20% increase in energy efficiency [2].

In contrast to the extraction of fossil fuels, the production of renewable fuels, either liquid fuels or electricity, requires land. However, land is also required for food production. In order to prevent or minimize the competition for land between the food and energy sectors, it is important to use the land for renewable energy production as efficient as possible. Or, in other words, land has to be used in such a way that maximal energy gains are achieved through minimal land use.

Several authors have compared the energy gain of different types of biomass. Cocco [3] compared the energy gains of several biofuel production chains in Europe, using average crop yields and averaged energy inputs. Other authors compared the net energy gain of crops through small-scale field trials (see for example [4]). Furthermore, many articles are devoted to the potential of biomass production (see for example [5]). However, little literature addresses the variations in net energy gain caused by both regional differences in yield and further processing of crops to bioenergy. Furthermore, little literature is available in which the net energy gain from biomass is compared to solar and wind energy on basis of the energy yield per unit of land used.

The objective of this article is to determine and to compare the variations in the energy production of selected renewable fuels in Europe, in order to shed a light on effective use of land. A case study is done to illustrate regional variations in the net energy gains.

2. Method and boundaries

In order to compare different renewable energy sources, the concept of energy density is used. Energy density is defined as 'the net energy production on a given area in a given time period'. The unit used here is GJ/ha/y. So, the net energy is the energy contained in the energy carrier such as electricity, biodiesel or bioethanol, annually produced on 1 ha, taking the inputs required to produce the carrier into account.

Table 1 lists the energy carriers of which the energy density was determined. For each energy carrier, 5 scenarios were drawn in order to obtain the range of energy densities found in Europe. The first 3 scenarios show the variation in energy densities caused by technical factors, the other 2 scenarios illustrate the consequences of geographical variations.

Technical factors include differences in agricultural practices, in energy use and efficiency of conversion of biomass to biofuels, or variations in the energy requirement for wind turbine and solar cell manufacturing. In addition, the energy inputs found in literature for these technical factors show variations, which is also taken into account. So, for these 3 scenarios the factors which are not directly related to geography are taken into account. Other parameters are not varied here. The scenarios are referred to as low (LO), average (AV), and high (HI).

The geographical scenarios are based on the AV scenario, and are referred to as AV− and AV+. These scenarios are used to determine the variations in energy density caused by geographical factors such as yield differences, as well as differences in wind speed and solar insolation.

2.1. Calculation energy density of biomass fuel

The calculation of the energy density of the energy carriers produced from biomass crops was done in 3 steps. First, the gross energy density (GED), defined as the energy contained in the

Table 2
Overview of the agricultural energy inputs for biomass for crop cultivation.

Energy carrier	Scenario	Yield[a] (t/ha/y)		Energy inputs (MJ/ha)													
		Wet	Dry	Ploughing[b]	Fertilization[c]		#	Weeding[d]		#	Harvesting[e]	#	Drying[f]	#	Chipping[g]	#
					Appl.	Manuf.		Appl.	Manuf.							
Biodiesel from rapeseed	LO	1.0	0.9	1650	65	2070	1	73	330	3	133	1	–	–	–	–
	AV	2.5	2.3	1350	65	4140	1	73	220	3	333	1	–	–	–	–
	HI	4.0	3.7	950	65	4968	1	73	110	3	534	1	–	–	–	–
Bioethanol from sugar beet	LO	20	4.8	1650	65	2206	1	73	330	6	527	1	–	–	–	–
	AV	50	12	1350	65	4412	1	73	220	6	1318	1	–	–	–	–
	HI	80	19	950	65	5294	1	73	110	6	2108	1	–	–	–	–
Electricity from wood[h]	LO	2	1	1650	65	941	1	–	–	–	709	5	1400	20	2400	5
	AV	6	3	1350	65	2259	1	–	–	–	2126	5	4200	20	7200	5
	HI	10	5	950	65	2824	1	–	–	–	3543	5	7000	20	12,000	5

[a] Moisture contents: rapeseed 8% [6]; sugar beet 76% [7]; wood 50% [8].
[b] Based on lowest and highest value given by [9]. Other literature sources [10,11 gives values in between.
[c] Fertilizer application 1.5 L diesel/ha [10], 43.3 MJ/L diesel. Manufacturing energy of fertilizers is taken as 50, 40, 30 MJ/kg N [11] for the low, average and high scenarios, respectively. Theoretical fertilizer demand, expressed in kg N/ha, is the amount of N extracted when the crop is harvested and depends on the crop yield, nitrogen content, and uptake efficiency. The nitrogen content of rapeseed is 2.7%, that of sugar beet 1%, the uptake efficiency of both is 50% (S. Nonhebel, pers. comm., September 23, 2008). The nitrogen content of tree leaves is 4%, uptake efficiency is 85%, and the total mass of the leaves is 40% of the stem mass [12]. In practice, only 83 and 46% of the nitrogen demand for rapeseed and sugar beet, respectively, is covered by artificial fertilizer (based on [6]). This is taken into account.
[d] Pesticides application 1.7 L diesel/ha [10], 43.3 MJ/L diesel. Pesticide manufacture data taken from [9].
[e] The energy requirements for harvesting are assumed to increase linearly with crop yield. Rapeseed: based on 3.0 L diesel[1]/t/ha for harvesting cereals ([13]; sugar beet: 0.61 L diesel/t/ha, average of [10,13]; wood: 177 MJ/t_{DM}, based on [11].
[f] Calculated by using $E = 1.39Y_{dry}$, with E the drying energy (GJ/t), and Y_{dry} (t/ha) the dry crop yield. Equation based on 2 models presented by [14].
[g] Based on 600 MJ/t_{DM} [11].
[h] The energy inputs for electricity from wood are given over a period of 20 years.

Table 3
Processes, energy inputs, and efficiencies of biomass conversion.

Biodiesel system			Bioethanol system			Electricity system	
Oil content seeds		40%[a]	Sugar content beet		16%[b]	Energy content wood	19 GJ/t[c]
Process	Efficiency (%)	Energy input (MJ/t oil)	Process	Efficiency (%)	Energy input (GJ/t EtOH)	Process	Efficiency (%)
Pressing and hexane extraction	98[a]	2300[d,e]	Fermentation, distillation, dehydration	38[a]	12 (LO) 20 (AV) 34 (HI)[f]	Combustion	29.1 (LO) 33.9 (AV) 38.8 (HI)
Transesterification	90[a]	6500[e,g]					
Energy content biodiesel		37.7 GJ/t[h]	Energy content bioethanol		26.8 GJ/t[f]		

[a] Ref. [3].
[b] Ref. [6].
[c] Ref. [21].
[d] Ref. [16].
[e] Ref. [17].
[f] Ref. [20].
[g] Ref. [18].
[h] Ref. [19].

energy carrier is calculated. Second, the inputs required to grow the crop and convert it to the desired energy carrier are calculated. The inputs taken into account in the agricultural phase are the direct energy inputs for ploughing and soil preparation, weeding and crop protection, fertilizer application, and harvesting. Furthermore, the indirect energy for fertilizer, pesticide, and fungicide production is taken into account. Table 2 gives an overview of the processes taken into account, and the corresponding energy inputs used. The energy inputs for conversion of the crop to the final energy carrier depend on the energy carrier that is produced. This process will be described in more detail later on. Third, the net energy density (NED) is calculated by subtracting the sum of the inputs from the GED.

For the LO, AV, and HI scenarios, the biomass yields used to determine the variations in energy density caused by technical factors are not varied between the scenarios. The rapeseed and sugar beet yields used for these scenarios are averages of the minimum and maximum yields obtained in all European countries in the period 2000–2007 [15]. For wood a yield of 2.5 t/ha/y is used for the AV scenario, half the maximum yield of 5.0 t/ha/y that can be obtained when no artificial fertilizers are applied [12].

For the AV− and AV+ scenarios for the 3 crops, the lowest and highest average crop yields obtained in Europe in the years 2000–2007 are used. As wood is not a regular crop, yield data for all European country are hard to obtain. Therefore, a minimum of 0.5 t/ha/y was used.

Focusing on the biodiesel production system, the agricultural phase includes ploughing, 1 round of fertilization, 3 rounds of weeding and crop protection, and finally harvesting. The energy inputs for this phase are listed in Table 2. In the conversion phase, the rapeseed oil is extracted by pressing, followed by hexane extraction. The oil thus obtained it then transesterificated to yield the biodiesel. Table 3 lists the efficiencies and energy inputs of the processes. As the variation in reported energy inputs per ton of oil is small, only a single value is used.

Production of bioethanol from sugar beet requires ploughing, 1 round of fertilization, 6 rounds of crop protection agent application, and finally harvesting the beets. Conversion of sugar beet to bioethanol starts with the production of green juice from the beets, followed by fermentation. The ethanol is then purified by distillation and dehydration [22]. Energy inputs for the conversion vary widely: 12–34 GJ/t bioethanol [20]. For this reason, these numbers are used for the HI and LO scenarios, respectively. Based on other data [3,22], 20 GJ/t ethanol is used for the AV scenario.

Willow and poplar cultivation for electricity is assumed to be grown in an extensive short rotation coppice (SRC) system. The plantation is operative for 20 years. Before planting trees, the soil is phoughed. Fertilization is done only in the first year of the plantation. After that, nitrogen is provided by falling leaves and natural nitrogen deposition. No weeding is done, wood is harvested and chipped every 4th year. The wood is dried until the moisture content has reached 15%, the maximum moisture content for direct combustion [23]. Then, it is co-combusted in a coal-fired power plant with an efficiency of 30–40%, depending on the scenario [24–26]. As the moisture in the wood lowers the efficiency, the efficiency of wood combustion is reduced to give the numbers given in Table 3 (calculated using [26]).

2.2. Calculation energy density of wind electricity

The calculation of the energy density is done in 2 steps. First, based on the electricity production of 1 wind turbine and the number of turbines that can be placed on 1 ha, the annual electricity output of all wind turbines placed on 1 ha is calculated (GED). Then, the lifecycle energy inputs are subtracted to give the NED. The calculations were carried out using the characteristics of 11 large, commercially available wind turbines listed in Table 4.

The electricity production of 1 wind turbine is calculated from its capacity and the number of annual full-load hours, the number of hours a turbine produces at full capacity. An empirical relation to determine the number of full-load hours h_f was derived by Hoogwijk et al. [36]:

$$h_f = 565V - 1745 \tag{1}$$

with V the wind regime (m/s), the average wind velocity.

Table 4
Overview of the characteristics of the wind turbines used to calculate energy density wind electricity [27–35].

		DeWind		Enercon			Nordex			Vestas		
		D6	D8	E-44	E-70	E-82	N80	N90	N100	V80	V82	V90
Rotor diameter	m	62	80	44	71	82	80	90	99.8	80	82	90
hub height	m	92	100	55	113	138	80	100	100	100	80	105
capacity	MW	1.25	2.00	0.90	2.30	2.00	2.50	2.50	2.50	2.00	1.65	3.00

The movement of rotor blades disturbs the wind flow, limiting the number of wind turbines that can be placed on 1 ha. The mutual distance between the turbines, expressed in rotor diameters *D*, is 7*D* in the prevailing wind direction and 4*D* in perpendicular to this direction (after [37]). Using 90% efficiency in converting wind energy to electricity, the GED can be calculated for each of the 11 turbines.

For the LO scenario, data from the wind turbine that produced the least electricity per hectare was used, for the HI scenario the turbine producing most electricity. The AV scenario uses the averaged data for all 11 wind turbines included here. For the 3 scenarios a wind regime of 8.5 m/s was assumed.

For the AV− and AV+ scenarios, wind regimes of 5.5 and 11.5 m/s at 50 m above sea level are used, respectively. Even though in some places in Europe the average wind speed is lower than 5.5 m/s, this number was chosen as the minimum level at which wind electricity production is economically viable [36]. The maximum value is based on the maximum average wind velocities found in Europe [38]. As the wind velocity increases with height and because the hub height of the turbines is more than 50 m, a correction for the wind velocity at hub height is done using the method described by [36].

Reported life cycle energy inputs for wind turbines show a large variation, from 5.8 TJ [39] to 84.2 TJ [40] for wind turbines with a rated power of 2 MW and a 3 MW, respectively. Other authors [41,42] give values in between these extremes, for turbines with capacities varying from 600 kW to 4.5 MW. For this article, data from [40] were used. The energy input for the production of a wind turbine was assumed to increase linearly from 27.2 TJ for a 850 kW turbine to 84.2 TJ for a 3 MW turbine. The assumed lifetime is 20 years.

2.3. Calculation energy density of solar electricity

The energy density of electricity produced by solar cells is calculated in a similar way as the energy density of wind electricity. The calculations are carried out for crystalline silicon solar cells, currently the dominant class of solar PV cells [43]. First, the GED is calculated, based on the electricity production of 1 solar cell and the number of solar cells that can be placed on 1 ha. Then the primary energy input for the production of the solar cell is averaged over the lifetime of the solar cell. The average annual energy input thus obtained is subtracted from the GED to obtain the NED.

The electricity annually generated by an optimally inclined solar cell of 1 kW_p, the energy output under standard test conditions, ranges between 1500 kWh along the southern borders of Europe and 600 kWh in Scandinavia [44]. For determining the influence of technical factors on energy density, 1000 kWh/kW_p is used, roughly equalling the electricity production in central European countries like (mid-) France, Austria, and Slovakia [44]. These numbers are based on a performance ratio of 0.75. The capacity per m^2 of installed solar cells varies between 90 and 145 W_p/m^2 for mono- and polycrystalline silicon cells [45–47]. These numbers are used for the LO and HI scenarios, respectively. For the AV scenario, an averaged value of 110 W_p/m^2 is used. When building a solar farm, the panels are placed inclinedly to maximize electricity output, so that a part of the surface is permanently excluded from direct sunlight. In practice, the surface area of the solar panels is maximally 40% of the total surface area of an electricity farm [48]. This percentage is however lower for most solar farms [49,50]. Therefore, a solar panel surface of 33% of the total surface area is used here.

García-Valverde et al. [51] list the primary energy inputs in the life cycle of a solar cell as determined by various literature sources, finding inputs in the range of 12.50–16.08 MWh_{th}/kW_p for solar cells with a lifetime of 25–30 years. For the calculation of the NED, energy inputs of 12.5, 14.25, and 16.0 MWh_{th}/kW_p are used for the HI, AV, and LO energy density scenarios, respectively. The assumed lifetime of a solar cell is 25 years.

In order to determine the geographical variation, the input data for the AV scenario are used, and combined with energy productions of 600 and 1500 kWh/kW_p for the scenarios AV− and AV+.

3. Results

The analysis of the net energy density (NED) of biodiesel, bioethanol, and electricity produced from biomass, as presented in Table 5, shows that except for the AV− scenario, and in the case of electricity from wood, the LO scenario, the NEDs are in the order of tens of GJ/ha/y.

In terms of absolute energy yields, the NEDs found for biodiesel from rapeseed are generally higher than those found for the other biofuels. Bioethanol from sugar beet shows the largest variation in terms of technical factors. The variations caused by geographic factors (crop yields) are comparable for all crops.

In terms of relative energy production, expressed in the ratio between energy output and energy input, electricity from wood gives the highest energy gain. This is mainly caused by low agricultural inputs. The relative energy production of bioethanol is the lowest of the 3 energy carriers compared. In the LO energy density scenario for bioethanol, the inputs are higher than the energy contained in the bioethanol.

Table 6 presents the results for wind electricity; Table 7 lists the results for the calculations of the energy density of solar electricity.

Comparing the results for all fuels shows that wind electricity has the highest net energy density, even though the gross energy

Table 5
Results energy density renewable fuels produced from biomass[a].

	Scenario			GED			Energy inputs						NED			O/I		
				GJ/ha/y			Agriculture GJ/ha/y			Conversion GJ/ha/y			GJ/ha/y					
		LO			30.6			8.4			8.0			14.2			1.87	
Biodiesel	AV−	AV	AV+	12.2	30.6	48.9	4.1	6.8	9.5	3.2	8.0	12.7	5.0	15.9	26.8	1.68	2.08	2.36
		HI			30.6			5.0			8.0			17.6			2.21	
		LO			81.5			11.0			103			−32.9			0.68	
Bioethanol	AV−	AV	AV+	32.6	81.5	130	5.5	8.9	13.4	24.3	60.8	97.3	2.8	11.8	20.7	1.09	1.17	1.19
		HI			81.5			6.7			36.5			38.3			1.92	
		LO			13.8			2.2			–			8.2			2.46	
Electricity	AV−	AV	AV+	3.2	16.1	32.2	0.48	2.1	4.1	–	–	–	2.1	10.5	21.1	2.75	2.89	2.91
		HI			18.4			2.1			–			12.9			3.33	

[a] Small round-off differences compared to Table 2 may occur in this table.

Table 6
Results energy density wind electricity, averaged data for 11 wind turbine types.

Scenario	h_f	Electricity production per turbine[a]		GED	Input	NED	O/I
	h/y	MWh/y	GJ/y	GJ/ha/y	GJ/ha/y	GJ/ha/y	
LO	3634	5397	19,430	493	129	903	7.03
AV−	1886	3487	12,552	728	177	552	3.13
AV	3866	7176	25,835	1500	177	1323	7.49
AV+	5846	10,848	39,053	2271	177	2094	11.9
HI	4058	8401	30,244	3224	233	1910	8.21

[a] 1 MWh = 3.6 GJ.

Table 7
Results energy density solar electricity.

Scenario	kWh/kWp	GED[a]		NED	O/I
		kWh/m^2/y	GJ/ha/y	GJ/ha/y	
LO	1000	29.7	1069	233	1.28
AV−	600	21.8	784	39	1.05
AV	1000	36.6	1307	562	1.75
AV+	1500	54.5	1960	1215	2.63
HI	1000	47.9	1723	1069	2.64

[a] 1 kWh = 3.6×10^{-3} GJ; 1 ha = 10,000 m^3.

densities of wind and solar electricity are comparable. Furthermore, geographical differences cause larger variations in NED than technical differences for most fuels. As a consequence, the NED of solar electricity is low in Northern European countries.

Table 8
Input and outcomes of case study.

Region	Input		NED	Distance driven[a]
			GJ/ha/y	10^4 km
Bioethanol from sugar beet				
SE	47[b]	t/ha/y	10.9	0.55
NL	62[c]	t/ha/y	15.5	0.78
ES	27[d]	t/ha/y	4.8	0.24
Biodiesel from rapeseed				
SE	2.9[e]	t/ha/y	18.8	1.1
NL	3.7[c]	t/ha/y	24.6	1.5
ES	1.3[f]	t/ha/y	7.2	0.43
Electricity from wood				
SE	2.4[g]	t/ha/y	12.3	2.0
NL	2.8[h]	t/ha/y	14.4	2.4
ES	0.5[i]	t/ha/y	2.5	0.41
Electricity from wind				
SE	7.0[j]	m/s	978	160
NL	6.8[j]	m/s	927	151
ES	5.1[j]	m/s	490	80
Electricity from solar PV				
SE	824[k]	kWh/kWp	356	58
NL	873[k]	kWh/kWp	421	69
ES	1473[k]	kWh/kWp	1213	198

[a] Based on energy consumption of 0.55 kWh/km for bioethanol in ICE [62], 0.46 kWh for biodiesel in ICE (calculated from bioethanol ICE, using engine efficiencies of 16 and 19% for bioethanol and biodiesel, respectively [63]), and 0.17 kWh/km for BEV (average of 0.11 and 0.23 kWh/km for short and long distance, [64]).
[b] Average yield of Kalmar province 2000–2008 [52].
[c] Average 2000–2008 [53].
[d] Spanish average 1999–2001 [54].
[e] Average of Östergötland, Kalmar, and Västra Götaland provinces 2000–2008 [52].
[f] Average Andalucia 1999–2001 [54].
[g] Ref. [55], assumed density: 0.35 t/m^3.
[h] Dutch average [56].
[i] Estimate, based on [57].
[j] Based on wind maps ([58] for SE, [59] for NL, [60] for ES), corrected for hub height.
[k] Ref. [61].

4. Case study: land use for transport fuels

To illustrate both regional variations and differences between energy carriers, a case study was carried out in which the calculated energy densities were used to determine the distance a vehicle can cover using the energy annually produced on 1 ha. This was done for 3 regions for all the energy carriers listed in Table 1.

The liquid fuels biodiesel and bioethanol are used in an internal combustion engine (ICE), electricity from wood combustion, wind and solar PV is used to drive a battery electric vehicle (BEV). The regions chosen are 3 rural areas in Sweden, the Netherlands, and Spain: Jönköping Province (SE) in Mid-Sweden, Groningen Province (NL) in the north of the Netherlands, and the Autonomous region of Murcia in the South-East of Spain (ES).

Using crop yields, wind regime and electricity production data for these regions combined with energy inputs from the AV scenario, the NED for each of the fuels was calculated, which was in turn used to calculate the distance a vehicle can cover. When the data for the specific provinces were not available, data for neighbouring provinces were used.

Table 8 lists the inputs, the energy densities, and the corresponding distances covered. The results show a wide variation, from 4100 to almost 2 million kilometers driven using the energy produced annually on 1 ha. Except for Spain, where electricity from solar PV annually yields most energy, wind energy is the most favourable option. Bioethanol from sugar beet is the poorest option in all of the regions.

5. Discussion

5.1. Fuels produced from biomass

Comparing the results for the renewable energy produced from biomass with energy produced by wind turbines or solar cells shows that the energy densities of the biomass-based energy is lowest. Or, in other words, 1 ha annually yields the lowest amounts of energy when it is used to grow energy crops.

When comparing the results found here to energy densities found in literature, it can be shown that the literature values ([3] for biodiesel and bioethanol, [16] for biodiesel, and [11] for wood) fall within the range of NEDs calculated here, at least when the biomass yields are comparable. The same holds for the energy output:input ratios.

When only looking at the energy inputs in the agricultural phase, the inputs found here are lower than, or in the lower parts of the range of numbers found in literature. This is declared by the system boundaries of this study, which excluded the energy consumption of seed production, transport of machinery and crops, and machine production.

On the other hand, the energy inputs for cultivation and conversion of the crops were fully allocated to the final product, resulting in overestimation of the inputs for bioethanol and biodiesel. Rapeseed oil extraction yields a pressing cake as a side product. Based on the price of biodiesel and pressing cake, approximately 25% of the inputs can be allocated to this side product [65]. However, [22] showed that allocation based either on mass, energy or market value maximally results in a 2.5% reduction of the energy inputs for bioethanol.

The advantage of the system boundaries and allocations used here is that a clear picture is obtained of how the energy densities of the crops are mutually related. Moreover, neither stretching system boundaries nor different allocation would alter the conclusion that the energy density of biofuels is up to a few orders of magnitude lower than those of electricity produced from wind or solar PV.

When comparing the LO–HI (technical factors) and AV+ − AV− (yield differences) scenarios, it can be seen that for biodiesel and electricity the largest variation is caused by yield differences. Even though sugar beet yields varied between 20 and 80 t/ha/y, technical factors are more important determinants for the energy density of bioethanol. This can be declared by the wide range of energy inputs in the conversion to bioethanol.

5.2. Electricity from wind

Comparing the energy density of wind electricity with the other energy densities found, the NED of wind electricity is the highest, not only in absolute numbers, but also in terms of the ratio energy output/input. Table 6 shows that the wind regime is the main factor determining the NED: the range of NEDs found for the LO–HI scenarios, based on technical differences between wind turbines, is considerably smaller than that of the scenarios in which the wind regime was varied.

A key assumption in the calculation of the energy density is the mutual distance of 7×4 rotor diameters between wind turbines. The distances given by [37] vary between 5×3 and 9×5 rotor diameters, 45% less and 60% more, respectively, than the mutual distance assumed here. Compared to this, the uncertainty in the results caused by assumptions about wind turbine efficiency, number of full-load hours, and energy input is small.

Comparing the results in terms of O/I rations found here with literature values shows that the numbers found here are low compared to those from [39,42], who found a ratio of 50 and 34.5, respectively, for wind regimes of 6.6 and 7.7 m/s. [66] showed that different studies yielded 2 orders of magnitudes of variation in energy intensity for wind electricity, caused by differences in location and turbine characteristics, scope of the study, and economies of scale. This may declare why the O/Is found here differ from those by the higher numbers found by [39,42].

5.3. Electricity from solar PV

Like the energy density of wind electricity, the NEDs found for solar electricity are in the order of 100–1000 GJ/ha/y. However, looking at the exact numbers, the NEDs of solar electricity are lower. From Tables 6 and 7, it can be seen that the GEDs of solar and wind electricity are comparable, but the energy inputs for solar cell manufacturing are considerably higher.

Comparing the different scenarios shows that the variation in energy densities for the 3 scenarios is mainly determined by the solar insolation, which in turn is determined by latitude. The influence of variations in solar cell efficiency and energy inputs on the energy density is small.

Comparing the O/I ratio for the HI energy density scenario found here to those calculated from energy payback times reported in literature, shows that the 3.03 found for South-Spain is higher than the 2.20 given by [51], but somewhat lower than the 3.6 found by [67]. The differences in energy gains reported in literature may be caused by the allocation of the energy consumption in the silicon manufacture process, as most silicon currently used is a side product from the semiconductor industry [67].

5.4. Case study

The case study shows that the distance driven using the energy annually produced on 1 ha is highest when using electricity produced by wind turbines, except for the region of Murcia in South-East Spain, where solar electricity is a more favourable option.

The distances covered by vehicles using the fuels produced from biomass is much lower, with bioethanol from sugar beet performing poorest. However, when comparing the NEDs of the fuels produced from biomass, those of bioethanol and electricity from wood are comparable. The differences in covered distances are explained by the efficiencies of the drivetrains of a BEV on the one hand, and a vehicle with an ICE on the other hand. Looking at the engines only, a combustion engine's efficiency is typically around 20%, an electric engine can be 80% efficient [63]. Apart from their higher fuel efficiency, an advantage of electric vehicles is that they do not cause local air pollution. Especially in cities, exhaust products of combustion engines cause air quality problems, affecting the health of the people living and working in cities.

Hybrid vehicles, combining traditional, liquid fuels and electricity may be suitable fuels for the transition towards BEVs. The hybrids currently available use gasoline to generate and store electricity, improving the vehicle's fuel efficiency. A next step towards BEVs may be plug-in hybrids that can be recharged from the electricity grid. This type of vehicle can be seen as a BEV with additional combustion engine [68].

A fuel left out of this study is hydrogen. Like electricity, this fuel is considered as one of the potential fuels for the future. Given a hydrogen production efficiency of 75% for the water electrolysis process [68] and a vehicle energy demand of 0.32 kWh/km [62], the distance that can be travelled using the electricity annually produced on 1 ha of land is lowered with 60% as compared with electric vehicles.

5.5. General remarks

In terms of energy density, the results and the case study showed that wind electricity often is the most favourable option for renewable energy production. Moreover, in contrast to growing biomass for energy purposes or constructing a solar farm, a major part of the land used for a wind farm can be used for other purposes, such as agriculture, as the towers of the turbines only occupy a fraction of the surface of the farm. An advantage of both wind and solar electricity is that they can be produced on marginal grounds which are not suitable for biomass production. As a consequence, no competition with food production will occur.

However, the choices for the introduction of renewable fuels do not only depend on energy density. Electricity production from wind or sun is hard to predict and shows a strong seasonal variation, leading to difficulties in balancing supply and demand of electricity. As biomass and biomass-based liquid biofuels can be

stored, these problems can be avoided. Furthermore, politics and economics also play a role.

In this study, only a limited number of crops, as well as electricity from wind and solar PV were taken into account. These fuels were chosen as reliable data were available, in contrast to some second-generation fuels. Other options include concentrated solar power, a new technology which may have a large potential in regions with mainly clear, unclouded skies. As most European countries are not cloudfree, this option was not considered here.

6. Conclusion

Comparing the energy densities of different renewable fuels showed that wind electricity annually yields most energy per hectare, followed by electricity produced by solar PV. Electricity production of wind and solar PV was comparable, but the energy input for solar cell production is much higher. Compared to wind and solar electricity, the energy densities of all 3 biomass-based fuels is a few orders of magnitude smaller. For the average scenario, the ratio of the energy densities is 100:42:1, for wind, solar, and biomass, respectively.

The 5 scenarios used for determining the energy densities showed considerable differences, depending mainly on variations in crop yield, wind regime, and irradiance (for biomass, wind, and solar PV, respectively). The variations in the energy densities of the biomass-based fuels caused by differences in energy inputs for agriculture and conversion were shown to be smaller than yield differences, except for bioethanol produced from sugar. For wind electricity, differences caused by technical differences were shown to be small, which is also the case for differences in the efficiency of solar cells.

Comparing the results with literature values shows that the results found here generally match literature values.

The case study showed that the energy density of wind electricity is highest for 2 of the 3 assessed regions, the exception being the region of Murcia, in South-East Spain, where solar PV is highest. From a mobility point of view, this means that a vehicle can cover the largest distance when powered by electricity from wind or sun.

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